

Heavy quarkonia mass-splittings in QCD: test of the $1/m$ -expansion and estimates of $\langle\alpha_s G^2\rangle$ and α_s

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Abstract

I present a more refined analysis of the mass-splittings between the different heavy quarkonia states, using *new double ratios* of exponential moments of different two-point functions. Then, I test the validity of the $1/m$ -expansion, extract $\alpha_s(M_Z) = 0.127 \pm 0.011$ from $M_{\chi_c(P_1^1)} - M_{\chi_c(P_1^3)}$, and provide a new estimate of the gluon condensate from $M_\psi - M_{\eta_c}$ and $M_{\chi_b} - M_\Upsilon$, which combined with the recent estimate from the τ -like decay sum rules in $e^+e^- \rightarrow I = 1$ hadrons data, leads to the *update average value* $\langle\alpha_s G^2\rangle = (7.1 \pm 0.9) \times 10^{-2} \text{ GeV}^4$ from the light and heavy quark systems. I also find $M_\Upsilon - M_{\eta_b} \approx 63_{+51}^{-29} \text{ MeV}$ implying the possible observation of the η_b in the Υ -radiative decay.

Talk given at QCD 96-Montpellier, 4-12th July 1996 and at the 28th ICHEP96-Varsaw, 25-31th July 1996, and based on the paper hep-ph/9512348 (to appear in Phys. Lett.B386, October 1996), which will be referred as SN.

1 The double ratio of moments

QCD spectral sum rule (QSSR) à la SVZ [1] (for a recent review, see e.g. [2]) has shown since 15 years, its impressive ability for describing the complex phenomena of hadronic physics with the few universal “fundamental” parameters of the QCD Lagrangian (QCD coupling α_s , quark masses and vacuum condensates built from the quarks and/or gluon fields). In the example of the two-point correlator:

$$\Pi_Q(q^2) \equiv i \int d^4x e^{iqx} \langle 0 | T J_Q(x) (J_Q(o))^\dagger | 0 \rangle, \quad (1)$$

associated to the generic hadronic current: $J_Q(x) \equiv \bar{Q}\Gamma Q(x)$ of the heavy Q -quark (Γ is a Dirac matrix which specifies the hadron quantum numbers), the SVZ-expansion reads:

$$\Pi_Q(q^2) \simeq \sum_{D=0,2,\dots} \sum_{\dim O=D} \frac{C^{(J)}(q^2, \mu) \langle O(\mu) \rangle}{(M_Q^2 - q^2)^{D/2}}, \quad (2)$$

where μ is an arbitrary scale that separates the long- and short-distance dynamics; $C^{(J)}$ are the Wilson coefficients calculable in perturbative QCD by means of Feynman diagrams techniques; $\langle O \rangle$ are the non-perturbative condensates of dimension D built from the quarks or/and gluon fields ($D = 0$ corresponds to the case of the naïve perturbative contribution). Owing to gauge invariance, the lowest dimension condensates that can be formed are the $D = 4$ light quark $m_q \langle \bar{\psi}\psi \rangle$ and gluon $\langle \alpha_s G^2 \rangle$ ones, where the former is fixed by the pion PCAC relation, whilst the latter is known to be $(0.07 \pm 0.01) \text{ GeV}^4$ from more recent analysis of the light [3] quark systems. The validity of the SVZ-expansion can be understood, using renormalon techniques (absorption of the IR renormalon ambiguity into the definitions of the condensates and absence of some extra $1/q^2$ -terms not included in the OPE) [4, 5] and/or by building renormalization-invariant combinations of the condensates (appendix of [6] and references therein). The SVZ expansion is phenomenologically confirmed from (among other applications) the unexpected accurate determination of the QCD coupling α_s [6]–[8] and from a measurement of the condensates [8] from semi-inclusive τ -decays. The previous QCD information is transmitted to the data through the spectral function $\text{Im}\Pi_Q(t)$ via the Källén–Lehmann dispersion relation (*global duality*) obeyed by the hadronic correlators, which can be improved from the uses of different versions of the sum rules [1],[2],[9]–[12]. In this paper, we shall use the simple duality ansatz parametrization: “*one narrow resonance*” + “*QCD continuum*”, from a threshold t_c , which gives a good description of the spectral integral in the sum rule analysis, as has been tested successfully in the light-quark channel from the $e^+e^- \rightarrow I = 1$ hadron data and in the heavy-quark ones from the $e^+e^- \rightarrow \psi$ or Υ data. We shall work with the relativistic version of the Laplace or exponential sum rules: [1, 10, 11, 12]:

$$\begin{aligned} \mathcal{L}_H(\sigma, m^2) &\equiv \int_{4m^2}^{\infty} dt \exp(-t\sigma) \frac{1}{\pi} \text{Im}\Pi_Q(t), \\ \mathcal{R}_H(\sigma) &\equiv -\frac{d}{d\sigma} \log \mathcal{L}_H(\sigma, m^2), \end{aligned} \quad (3)$$

where the QCD expression known to order α_s is given (without expanding in $1/m$) in terms of the pole mass $m(p^2 = m^2)$,¹ and contains the gluon condensate $\langle \alpha_s G^2 \rangle$ correction to leading order. To this order, the gluon condensate is well-defined as the ambiguity only comes from higher order terms in α_s , which have, however, a smaller numerical effect than the one from the error of the phenomenological estimate of the condensate. $\sigma \equiv \tau \equiv 1/M^2$ (notations used in the literature) is the exponential Laplace sum rule variable; H specifies the hadronic channel studied. In principle, the pair (σ, t_c) is free external parameters in the analysis, so that the optimal result should be

¹For consistency, we shall work with the two-loop order α_s expression of the pole mass [13].

insensitive to their variations. *Stability criteria*, which are equivalent to the variational method, state that the best results should be obtained at the minimas or at the inflexion points in σ , while stability in t_c is useful to control the sensitivity of the result in the changes of t_c -values. These stability criteria are satisfied in the heavy quark channels studied here, as the continuum effect is negligible and does not exceed 1% of the ground state contribution [2, 11], such that at the minimum in σ , one expects to a good approximation:

$$\min_{\sigma} \mathcal{R}(\sigma) \simeq M_H^2. \quad (4)$$

Moreover, one can *a posteriori* check that, at the stability point, where we have an equilibrium between the continuum and the non-perturbative contributions, which are both small, the OPE is still convergent and validates the SVZ-expansion. The previous approximation can be improved by working with the double ratio of moments ² :

$$\mathcal{R}_{HH'}(x) \equiv \frac{\mathcal{R}_H}{\mathcal{R}_{H'}} \simeq \frac{M_H^2}{M_{H'}^2}, \quad (5)$$

provided that each ratio of moments stabilizes at about the same value of σ . In this case, there is a cancellation of the different leading terms like the heavy quark mass (and its ambiguous definition used in some previous literatures), the negligible continuum effect (which is already small in the ratio of moments), and each leading QCD corrections.

2 Test of the $1/m$ -expansion

For this purpose, we use the complete *horrible* results expressed in terms of the pole mass to order α_s given by [11] and checked by various authors [2], which we expand in series of $1/m$ with the help of the Mathematica program. By comparing the complete and truncated series in $1/m$, one can notice that, at the c and b mass scales, the convergence of the $1/m$ -expansion is quite bad due to the increases of the numerical coefficients with the power of $1/m$ and to the alternate signs of the $1/m$ series. This feature invalidates the analysis in Ref. [14].

3 Balmer-mass formula

The Balmer formula derived from a non-relativistic approach ($m \rightarrow \infty$) of the Schrödinger levels reads for the S_1^3 vector meson [16] (see also [17],[18]):

$$M_{S_1^3}^{static} \simeq 2m \left[1 - \frac{2}{9} \alpha_s^2 + 0.23 \frac{\pi}{(m\alpha_s)^4} \langle \alpha_s G^2 \rangle \right]. \quad (6)$$

It is instructive to compare this result with the mass formula obtained from the ratio of moments within the $1/m$ -expansion. Using the different QCD corrections, one obtains the mass formula at the minimum in σ of \mathcal{R} :

$$M_{\Upsilon} \simeq 2m_b \left(1 + \frac{\pi}{27} \alpha_s^2 \right) M_{S_1^3}^{static}, \quad (7)$$

at the value:

$$\sqrt{\sigma_{coul}} \simeq \frac{9}{4m\alpha_s\sqrt{\pi}} \simeq 0.85 \text{ GeV}^{-1}. \quad (8)$$

²This method has also been used in [15] for studying the mass splittings of the heavy-light quark systems.

One can recover by identification in the *static limit* ($m_b \rightarrow \infty$) the previous Balmer formula, but a new extra α_s^2 correction due to the v^2 (finite mass) terms in the free part appears here (for some derivations of the relativistic correction in the potential approach see [21], [22]), and tends to reduce the coulombic interactions. On the other hand, at the b -quark mass scale, the dominance of the gluon condensate contribution indicates that the b -quark is not enough heavy for this system to be coulombic rendering the non-relativistic potential approach to be a crude approximation at this scale. The extension of this comparison to the cases of the S_1^3 - S_0^1 hyperfine and S - P splittings is not very conclusive, as in the former, one needs an evaluation of the correlator at the next-next-to-leading order for a better control of the α_s^2 terms, while, in the latter there is a discrepancy for the coefficients of the gluon condensate in the two approaches, which may reflect the difficulty of Bell-Bertlmann [10, 11] to find a bridge between the field theory à la SVZ (flavour-dependent confining potential) and the potential models (flavour-independence).

4 Leptonic width and wave function

Using the sum rule \mathcal{L}_H and saturating it by the vector S_1^3 state, we obtain, to a good approximation, the sum rule:

$$M_V \Gamma_{V \rightarrow e^+ e^-} \simeq (\alpha e_Q)^2 \frac{e^{2\delta m M_V \sigma}}{72 \sqrt{\pi}} \frac{\sigma^{-3/2}}{m} \left[1 + \frac{8}{3} \sqrt{\pi \sigma} m \alpha_s - \frac{4\pi}{9} \langle \alpha_s G^2 \rangle m \sigma^{5/2} \right], \quad (9)$$

where e_Q is the quark charge in units of e ; $\delta m \equiv M_V - 2m$ is the meson-quark mass gap. In the case of the b -quark, we use [13] $\delta m \simeq 0.26$ GeV, and the value of σ_{min} given in Eq. (8). Then:

$$\Gamma_{\Upsilon(S_1^3) \rightarrow e^+ e^-} \simeq 1.2 \text{ keV}, \quad (10)$$

in agreement with the data 1.3 keV. However, one should remark from Eq. (9), that the α_s correction is huge and needs an evaluation of the higher order terms (the gluon condensate effect is negligible), while the exponential factor effect is large, such that one can *reciprocally* use the data on the width to fix either α_s or/and the quark mass³. In the non-relativistic approach, one can express the quarkonia leptonic width in terms of its wave function $\Psi(0)_Q$, from which, one can deduce:

$$16\pi |\Psi(0)|_Q^2 \left(1 - 4C_F \frac{\alpha_s}{\pi} \right) \simeq 18.3 \text{ GeV}^3. \quad (11)$$

Using the expression of σ_{coul} , one can find that, to leading order, the two approaches give a similar behaviour for $\Psi(0)_Q$ in α_s and in m and about the same value of this quantity. However, one should notice that in the present approach, the QCD coupling α_s is evaluated at the scale σ as dictated by the renormalization group equation obeyed by the Laplace sum rule [12] but *not* at the resonance mass!

5 Gluon condensate from $M_{\psi(S_1^3)} - M_{\eta_c(S_0^1)}$

The value of σ , at which, the S -wave charmonium ratio of sum rules stabilize is: [11]: $\sigma \simeq (0.9 \pm 0.1) \text{ GeV}^{-2}$. We use the range of the charm quark pole mass value $m_c \simeq 1.2$ -1.5 GeV to

³Larger value of the heavy quark mass at the two-loop level corresponding to a negative value of δm , would imply a much smaller value of the leptonic width in disagreement with the data.

order α_s accuracy [13]⁴, and the double ratio of the vector $V(S_1^3)$ and the pseudoscalar $P(S_0^1)$ moments, which controls the ratio of the meson mass squared. The exact expressions of the relativistic, Coulombic and gluon condensate lead respectively to corrections about 0.5, 2 and 7 % of the leading order one. One can understand from the approximate expressions in $1/m$ that the leading corrections appearing in the ratio of moments cancel in the double ratio, while the remaining ones are relatively small. However, the expansion is not convergent for the α_s -term at the charm mass. Using for 4 flavours [13]: $\alpha_s(\sigma) \simeq 0.48_{-0.10}^{+0.17}$, and the experimental data [24]: $\mathcal{R}_{VP}^{exp} = 1.082$, one can deduce the value of the gluon condensate:

$$\langle \alpha_s G^2 \rangle \simeq (0.10 \pm 0.04) \text{ GeV}^4. \quad (12)$$

We have estimated the error due to higher order effects by replacing the coefficient of α_s with the one obtained from the effective Coulombic potential, which tends to reduce the estimate to 0.07 GeV^4 . We have tested the convergence of the QCD series in σ , by using the numerical estimate of the dimension-six gluon condensate $g\langle f_{abc}G^aG^bG^c \rangle$ contributions given in [20]. This effect is about 0.1% of the zeroth order term and does not influence the previous estimate in Eq. (12), which also indicates the good convergence of the ratio of exponential moments already at the charm mass scale in contrast with the $q^2 = 0$ moments studied in Ref. [1, 25]. We also expect that in the double ratio of moments used here, the radiative corrections to the gluon condensate effects (available in the literature [26]) are much smaller than in the individual moments, such that they will give a negligible effect in the estimate of the gluon condensate.

6 Charmonium P -wave splittings

The analysis of the different ratios of moments for the P -wave charmonium shows [10, 11, 20] that they are optimized for: $\sigma \simeq (0.6 \pm 0.1) \text{ GeV}^{-2}$. The predictions for the scalar P_0^3 - axial P_1^3 and the tensor P_2^3 -axial P_1^3 mass splittings, given in SN, are satisfactory within our approximation.

7 α_s from the P_1^1 - P_1^3 axial mass splitting

The corresponding double ratio of moments has the nice feature to be independent of the gluon condensate to leading order in α_s and reads:

$$\frac{M_{P_1^1}^2}{M_{P_1^3}^2} \simeq 1 + \alpha_s \left[\Delta_\alpha^{13}(\text{exact}) = 0.014_{+0.008}^{-0.004} \right]. \quad (13)$$

The recent experimental value 3526.1 MeV of the P_1^1 mass denoted by $h_c(1P)$ in the PDG compilation [24] almost coincides with the one of the center of mass energy, as expected from the short range nature of the spin-spin force⁵. Using a naïve exponential resummation of the higher order α_s terms, we deduce:

$$\alpha_s(\sigma^{-1} \simeq 1.3 \text{ GeV}) \simeq 0.64_{-0.18}^{+0.36} \pm 0.02 \quad (14)$$

which implies:

$$\alpha_s(M_Z) \simeq 0.127 \pm 0.009 \pm 0.002, \quad (15)$$

⁴For a recent review on the heavy quark masses, see e.g. [23, 24].

⁵See e.g. [30].

where the error is much bigger than the one from LEP and τ decay data, but its value is perfectly consistent with the latter. The theoretical error is mainly due to the uncertainty in Δ_α , while a naïve resummation of the higher order α_s terms leads the second error. Though inaccurate, this value of α_s is interesting for an alternative derivation of this fundamental quantity at lower energies, as it can serve for testing its q^2 -evolution until M_Z . *Reciprocally*, using the value of α_s from LEP and τ -decay data as input, one can deduce the prediction of the center of mass (c.o.m) of the P_J^3 states given in Table 2 of SN.

8 $\Upsilon - \eta_b$ mass splitting

For the bottomium, the analysis of the ratios of moments for the S and P waves shows that they are optimized at the same value of σ , namely [11]: $\sigma = (0.35 \pm 0.05) \text{ GeV}^{-2}$, which implies for 5 flavours: $\alpha_s(\sigma) \simeq 0.32 \pm 0.06$. We shall use the conservative values of the two-loop b -quark pole mass: $m_b \simeq 4.2 - 4.7 \text{ GeV}$. The splitting between the vector $\Upsilon(S_1^3)$ and the pseudoscalar $\eta_b(S_0^1)$ can be done in a similar way than the charmonium one. One should also notice that, to this approximation, the gluon condensate gives still the dominant effect at the b -mass scale (0.2% of the leading order) compared to the one .08% from the α_s -term. However, the $1/m$ series of the QCD α_s correction is badly convergent, showing that the static limit approximation can be quantitatively inaccurate in this channel. Therefore, one expects that the corresponding prediction of $(13_{+10}^{-7}) \text{ MeV}$ is a very crude estimate. In order to control the effect of the unknown higher order terms, it is legitimate to introduce into the sum rule, the coefficient of the Coulombic effect from the QCD potential [18], which leads to the “improved” final estimate:

$$M_\Upsilon - M_{\eta_b} \approx (63_{+51}^{-29}) \text{ MeV}, \quad (16)$$

implying the possible observation of the η_b from the Υ radiative decay.

9 Gluon condensate from $M_\Upsilon - M_{\chi_b}$

As the S and P wave ratios of moments are optimized at the same value of σ , we can compare directly, with a good accuracy, the different P states with the $\Upsilon(S_1^3)$ one. As the coefficients of the α_s^2 corrections, after inserting the expression of σ_{coul} , are comparable with the one from the Coulombic potential, we expect that the prediction of this splitting is more accurate than in the case of the hyperfine. The different double ratios of moments leads to the predictions of the χ_b states P_0^3 , P_1^3 , P_2^3 given in Table 2 of SN in good agreement with the data, if one uses the value of α_s [19] and of the gluon condensate obtained previously. Reciprocally, one can use the data for re-extracting *independently* the value of the gluon condensate. As usually observed in the literature, the prediction is more accurate for the center of mass energy, than for the individual mass. The corresponding numerical sum rule for:

$$(M_{\chi_b}^{c.o.m} - M_\Upsilon) / M_\Upsilon \quad (17)$$

is due to $+(1.53_{-0.42}^{+0.26}) \times 10^{-2}$ of the relativistic effects, $+(1.20_{-0.2}^{+0.1}) \times 10^{-2}$ of the Coulombic and $+(0.28_{-0.06}^{+0.08}) \text{ GeV}^{-4} \langle \alpha_s G^2 \rangle$ of the gluon condensate ones. It leads to:

$$\langle \alpha_s G^2 \rangle \simeq (6.9 \pm 2.5) \times 10^{-2} \text{ GeV}^4. \quad (18)$$

We expect that this result is more reliable than the one obtained from the $M_\psi - M_{\eta_c}$ as the latter can be more affected by the non calculated next-next-to-leading perturbative radiative corrections than the former.

10 Update average value of $\langle\alpha_s G^2\rangle$

Considering the most recent estimate $(7 \pm 1) \times 10^{-2} \text{ GeV}^4$ from $e^+e^- \rightarrow I = 1$ hadrons data using τ -like decay [3] as an update of the different estimates from the light quark systems (see Table 2 of SN), we can deduce from Eqs. (12) and (18), the *update average* from a global fit of the light and heavy quark systems:

$$\langle\alpha_s G^2\rangle \simeq (7.1 \pm 0.9) \times 10^{-2} \text{ GeV}^4. \quad (19)$$

This result confirms the claim of Bell-Bertlmann [10, 11] stating that the SVZ value [1] has been underestimated by about a factor 2 (see also [27, 28]). More accurate measurements of this quantity than the already available results from τ -decay data [8] are needed for testing the previous estimates from the sum rules.

11 Conclusions

We have used *new double ratios* of exponential sum rules for directly extracting the mass-splittings of different heavy quarkonia states, the value of the gluon condensate and of the QCD coupling α_s . Our numerical results are summarized in Eqs. (12), (18) and (19) and in Table 2 of SN, where in the latter a comparison with different estimates and experimental data is done. We have also succeeded to derive the non-relativistic Balmer formula from the sum rule, using a $1/m$ -expansion, where we have also included new relativistic corrections due to finite value of the quark mass. However, this expansion does not converge at the c and b quark mass scale.

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